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Abstract

MIT and PPPL have joined together to fabricate a high-power lower hybrid current drive (LHCD) system for supporting steady-state AT regime research on Alcator C-Mod. The goal of the first step of this project is to provide 1.5 MW of 4.6 GHz RF power to the plasma with a compact launcher which has excellent spectral selectivity and fits into a single C-Mod port. Some of the important design, construction, calibration and testing considerations for the launcher leading up to its installation on C-Mod are presented here.

1. Introduction

The objective of the lower hybrid current drive experiments on C-Mod is to supplement bootstrap current drive to develop attractive steady-state regimes - those with high bootstrap current (≥ 70%), operating near the no-wall β_N stability limit (~ 3) and exhibiting good energy confinement (H_H ~ 1 - 2) - which scale to desirable regimes for ITER [1]. Good real time spectral control for selecting the LHCD current profile in the plasma over several current diffusion times (t_d ~ 1 sec in C-Mod) is required to accomplish this objective. A novel compact launcher design with 24 columns and 4 rows of waveguides, 0.55 cm x 6.0 cm each, has been developed to deliver 1.5 MW to the plasma to meet this challenge within the space constraints of the C-Mod port (20 cm wide) [2]. Some of the important design, construction and testing considerations in realizing a suitable launcher for C-Mod are presented in the sections that follow.

2. Launcher Design Details

A cross-section through a column of the launcher system is shown in Fig. 1. The system is composed of three main sections - coupler, forward waveguide assembly (FWG) and rear waveguide assembly (RWG). Only the coupler section of the waveguide is in vacuum. An important aspect of the design is that the three sections are joined together using compliant aluminum gaskets that are located on the air side of the launcher to avoid potential gasket arcing in the vacuum.

The coupler is made from 4 blocks of titanium (one for each row) using a plunge electro-discharge machining (EDM) technique for making very close tolerance waveguide channels. Alumina windows are also precisely machined and are then brazed into the couplers as a vacuum boundary. These windows are located 12 - 15 cm away from the guide mouth to minimize material deposition from the plasma. Also, $f < f_{ce}$ inside the window to avoid electron cyclotron resonance breakdown inside the vacuum guide. Finally, the coupler is attached via a gold seal to the FWG to complete the vacuum boundary.

Compressing the gold seal and the aluminum gasket to the FWG simultaneously requires careful analysis to meet the requirement that proper compression be sustained from liquid nitrogen temperature (- 196° C from possible cryostat failure) to machine bakeout temperature (+ 150° C). First, the gold seal compression is ~ 220 MPa as required for achieving 2.63 kN/cm of the gold seal. This gives a strain range of 0.0028 (Fig. 2) under elastic deformation which multiplied by the depth of the gold seal (0.375 mm) gives a maximum allowable thermal deformation difference between the gold seal and the groove of 1.07` microns over the 346° C temperature range. For this temperature range the actual relative deformation is only 0.41 microns and thus the gold seal will not unload and will maintain vacuum. To attain 2.63 kN/cm sealing pressure, each of the (28) #10-32 bolts must be loaded (or stressed) to 340 MPa. To minimize the additional bolt stress required to compress the gasket, a novel plunge EDM produced aluminum gasket design has been developed which has a large compression range (up to ~ 0.30 mm) with a total compression force of ~ 170 MPa on the bolts (Fig. 3). The combined bolt stress of ≈ 510 MPa is ~ 1/2 the yield stress of the Inconel 718 bolts and thus the bolts have ample margin.

Additional stress in the bolts resulting from differential expansion between the titanium coupler flange and the Inconel bolts is mediated by placing 9 mm long stainless steel bushings under the bolt heads. A stress on the bolts of ~ 550 MPa set at 150° C then gradually increases to ~ 830 MPa at - 196° C, a value still well within the allowable for the bolt. Finally, in order to possibly avoid such extreme temperature excursions, cooling channels and heating elements are designed into the flange of the FWG to which the coupler is attached.

The FWG and RWG are formed from stacked plates with channels machined in them. These are held together with bolts and are similar in design concept to the commercial power splitter used for the LH system on PBX [3]. The FWG is ~ 1.2 m long to allow entry through the C-Mod port and is made of stainless steel plates to minimize disruption forces in the high magnetic field of C-Mod. The guides are copper plated to minimize losses and have H-plane tapers precisely located to increase the height of the guides to 6 cm (from the 4.75 cm width of the standard WR 187 guide) and to adjust the phase shifts of the two top (bottom) guides of each column to have the same phase at the mouth of the coupler.

The RWG serves as the power distribution assembly from the sources to all 96 waveguides. Commercial waveguide components (WR 187) are used to feed each column via two E-plane transformers (top/bottom in Fig. 1) which in turn lead to 3 dB power splitters which complete the split of power to the four guides of the column. Considerable development went into specifying the splitter design, employing both analysis and prototyping [4,5]. The addition of a post in the splitter slot between guides gives a much broader frequency range for the desired 3 dB split and much lower power return to the 4th leg of the splitter (< - 40 dB). Two adjacent columns are fed by each of the 12 sources that are phase programmable permitting the control of the spectrum in real time [6]. The phase between the two adjacent columns is also adjustable with a manual high power phase shifter to provide even greater control of the spectrum.

3. Construction Issues

Much of the construction work was straight forward after completion of the prototype studies. However, some issues did arise relative to window brazing, plating of the coupler and the FWG stainless steel plates, and mating between the plates of the FWG. The windows for a first set of couplers were brazed using a technique employing Ti alloy 6242 that was developed for PLT and used successfully for PBX and ASDEX [7]. The braze was made with a silver ABA alloy at 920° C and subsequent examination revealed surface cracking around the perimeter of the alumina brick faces. This problem had also been observed for the initial braze process for the FTU LH windows [8]. Analysis and braze prototyping led to the conclusion that the published coefficient of thermal expansion (CTE) data for either the Ti or Al_2O_3 was in error. As illustrated in Fig. 4, CTE measurements of Ti 6242 alloy and alumina using two different instruments (1 at Anter [9], and 2 at PPPL with a second Anter instrument) show a much larger ratio of the CTE between Ti and alumina than indicated for the published data: CTE_{Ti}/CTE_{Al2O3} = 1.35 (1), 1.33 (2), 1.11 (published), respectively, for 500° C. If we assume that the measurement made by Anter is the most accurate, then all of the discrepancy is in the Ti 6242 published data. This larger actual CTE for Ti makes the brazing process more difficult and has led us to develop a process at lower temperature. A second set of couplers is now being brazed with CuSil alloy at a reduced temperature of 820° C. Plating of the coupler will be performed after the brazing is completed with care being taken to mask the braze zone.

The plating of the steel plates of the FWG was designed to be performed prior to final machining of the mating surfaces to assure a close fit between the plates. Subsequent machining of the mating surfaces and the ends of the assembled plates resulted in some peeling of the plating. Therefore, the design was changed to have no machining after plating and steps were taken to assure proper thickness of the plates without machining and proper plating adherence. In particular, technical support was supplied to the plating company to make measurements during the plating process to obtain the same overall thickness for each plate, including the plating thickness, as obtained from the original machining process and then all plates were baked out to 500° C to assure that the plating would not blister. The plates were then polished and reassembled. The resulting unevenness of the guide ends (~ ± 0.05 mm) was accommodated by the relatively large compression range of the aluminum gasket.

4. Calibrations and Testing

Many calibrations and tests were performed on prototypes and the final launcher components to assure compliance with design requirements. A few of the important results are outlined here.

The window thickness required for transmission of the 4.6 GHz power was set with a transmission test fixture [4]. The reflected power dip versus frequency was then used to set the thickness required taking into account the actual value of the dielectric constant for the alumina used. The entire reflected power curve versus frequency is described very well by the equation for a plane wave impinging on a dielectric slab [10].

The FWG waveguide losses were found to be high (~ 2.4 dB/m) after plating but were reduced with polishing to ~ 0.3 ± 0.075 dB/m except for 2 channels which were reduced to 0.45 dB/m. Some of the loss variation was undoubtedly due to the unevenness of the guide ends (~ ± 0.05 mm) and the use of temporary gaskets. However, the relative loss between guides is acceptable and the larger losses for selected guides can be ameliorated with input power adjustments.

A very important calibration was the measurement of the power split for the top/bottom splitters (Fig. 1). The results are shown in Fig. 5. The split is generally quite good between rows with differences in the range of 0.2 ± 0.15 dB (bi-directional between rows). It should also be noted that the losses generally increase in groups of eight columns as the RWG input flange moves farther from the splitter region. Overall, the loss in the aluminum stacked plate guides was ~ 0.3 dB/m as was also the case for the commercial splitter used on PBX (gaskets were not used for the measurements of Fig. 5 which resulted in some additional loss). Again, some compensation for the differences in loss between the 12 column pairs can be made by adjusting the source powers.

Several tests have also been performed at high power to quantify the power handling capability of the launcher components. To match the maximum voltage and current conditions everywhere in a guide that would be experienced at selected locations for 20% reflected power from the plasma, the desired test power level into matched load is ~ 3 times the design power per guide of ~ 15 kW. The initial braze prototype coupler was tested to ~ 90 kW/guide for 0.14 sec in air and no arcing was observed even for the window with micro-fissures. The FWG channels supported ~ 70 kW for 0.5 sec. Presently, tests are ongoing for the combined FWG-RWG combination using the aluminum gaskets. These tests require a two dummy load arrangement as shown in Fig. 6. Many of the channels have already been tested successfully to powers of ~ 90 kW at the input transformer or ~ 45 kW after the split to two guides.

These high power tests are very encouraging and demonstrate the viability of the designs for the FWG, RWG and the aluminum gasket. The projected power density for the launcher is ~ 4.1 kW/cm^2 at the design power delivered to the plasma of 1.5 MW. However, the ultimate power limit for the launcher will be set primarily by the power handling capability of the vacuum region of the coupler which is exposed to the plasma and its surrounding relatively elevated neutral pressure.

5. Conclusion

Tests show that the C-Mod LH launcher should support the 1.5 MW design power capability into the coupler through 96 guides. The in-vessel region of the coupler will likely set the power limit for AT regimes, this limit depending on the neutral pressure in the coupler. The real-time phase/spectral control via the commercial feed hardware and splitter arrangement will provide considerable flexibility in selecting the LH contribution to the current profile on C-Mod.

Acknowledgements

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Figures

Fig. 1. Lower hybrid launcher cross-section as installed on C-Mod.

Fig. 2. Stress-strain curve for gold.

Fig. 3. Aluminum gasket compression curve with gasket cross-section.

Fig. 4. Coefficient of thermal expansion for Ti and Al_2O_3. (Curves labled with 1 and 2 are average of measured values with instrument 1 and 2; Coors and Mil HDBK are manufacturer's published values.)

Fig. 5. Split power outputs for top and bottom splitters.

Fig. 6. High power test setup for combined FWG and RWG tests.

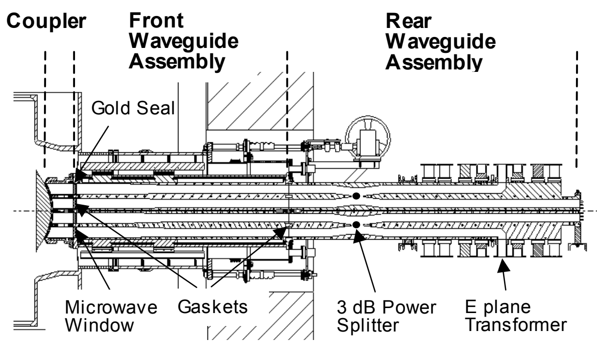
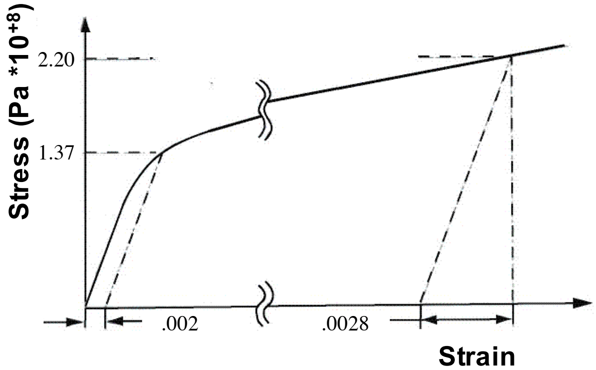

Coupler
Front
Waveguide
Assembly
Rear
Waveguide
Assembly
Gold Seal
Microwave
Window
Gaskets
3 dB Power
Splitter
E plane
Transformer

Figure 1



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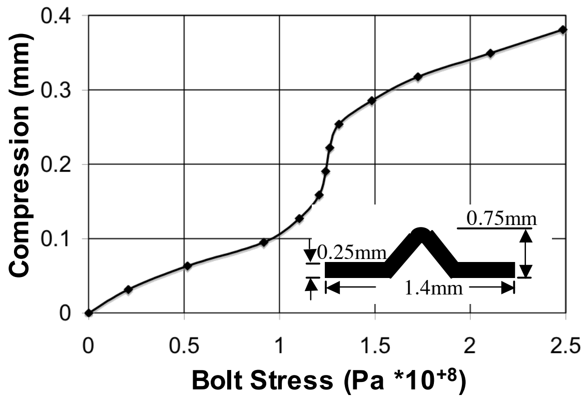
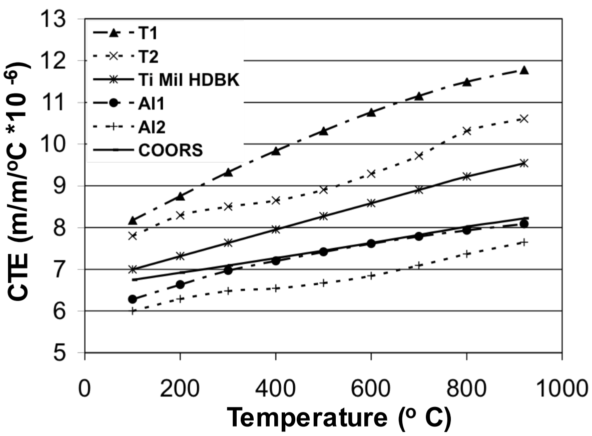

0.4
0.3
0.2
0.1
0
Compression (mm)
0
0.5
1
1.5
2
2.5
Bolt Stress (Pa *10+8)
0.25mm
0.75mm
1.4mm

Figure 3



T1
T2
Ti Mil HDBK
Al1
Al2
COORS
CTE (m/m/ºC *10 -6)
13
12
11
10
9
8
7
6
5
0
200
400
600
800
1000
Temperature (º C)

Figure 4

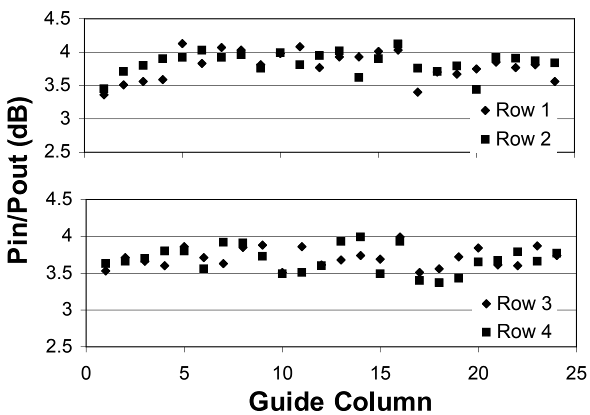

4.5
4
3.5
3
2.5
Row 1
Row 2
4.5
4
3.5
3
2.5
Row 3
Row 4
0
5
10
15
20
25
Pin/Pout (dB)
Guide Column

Figure 5

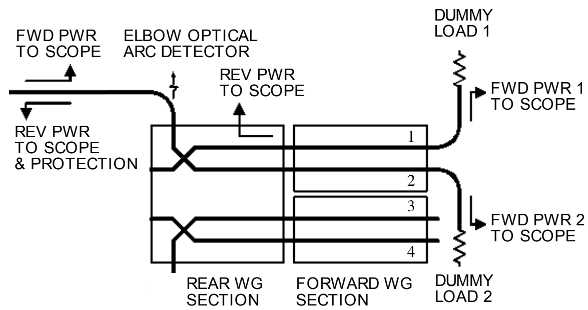

FWD PWR
TO SCOPE
ELBOW OPTICAL
ARC DETECTOR
REV PWR
TO SCOPE
DUMMY
LOAD 1
FWD PWR 1
TO SCOPE
REV PWR
TO SCOPE
& PROTECTION
1
2
3
4
FWD PWR 2
TO SCOPE
REAR WG
SECTION
FORWARD WG
SECTION
DUMMY
LOAD 2

Figure 6

External Distribution

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